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Profitability of wind energy investments in China using a Monte Carlo approach for the treatment of uncertainties

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ABSTRACT

China is the global leader in terms of installed wind capacity. Further, wind energy development is expected for the next years and decades to meet the continuously increasing electricity demand and the need of using clean domestic energy. Since 2009 China is divided into four geographical regions, each assigned with a different benchmark on-grid tariff. Moreover the existing infrastructures are not equally developed throughout the country, making investment decisions more complicated and risky. The scope of this paper is to apply an innovative methodology and evaluate the attractiveness of each region for wind energy development, by taking into consideration all relevant investment risks, such as wind potential, wind curtailment, access to the grid and macroeconomic parameters. To this purpose a Monte Carlo simulation approach, integrated into a typical financial model, is implemented in each of the four regions, performing many hundreds of iterations, each characterized by a randomly selected set of the examined uncertain parameters. This approach intends to provide information to private investors doing a first exploratory research in the huge country's area in order to decide whether and where to invest, as well as to policy makers to help them assess critical policy parameters and investigate different scenarios of wind energy development. The evaluation of the current framework for wind energy development in China verifies that the existing system of feed-in tariffs in China is very effective for the balanced deployment of wind energy in the whole country. However, it is shown that the risk of curtailment and grid accessibility may significantly reduce the potential profitability of wind energy investments in all four regions. Priority for development of infrastructures should be given in isolated northern windy areas with high-accumulation of wind farms.

Contents

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[1] In memory of professor Kostas Rados (1965–2013).

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1. Introduction

China with 1.4 billion people living on 9.6 million km^2 of land, with rich natural resources and cultural deposits, is the most attractive place in the world for both visitors and investors, especially since the implementation of the economic reform and open-up policy in 1978 [1]. Recently China emerged as a booming economy, which brought not only numerous business opportunities but also investors from all over the world. In fact China is undergoing rapid economic development, industrialization and continuous improvement of living standards, which is resulting in sharply rising energy consumption. Contrary to the trend recorded in developed countries, future energy demand in China will keep growing at a rapid rate, imposing a high pressure on the power supply side. Though China was a net oil exporter before 1993, it has become today the second largest oil importer in the world. Moreover, the country is already the world's largest emitter of greenhouse gases. However, China's per capita emissions are still far behind those recorded in most developed countries.

In this framework wind energy is considered as a very promising field for Chinese economy, which may significantly contribute toward energy independence and CO_2 emissions reduction. Despite the economic crisis in Europe, the wind sector is still one of the world's fastest growing energy-related industries. By the end of 2013 the cumulative wind capacity reached 318 GW in the world, with 35.5 GW of annual new capacity added in 2013. China is the leading global player in the wind energy sector, ahead of USA, with its total capacity reaching 91.4 GW at the end of 2013, with 16.1 GW added in 2013 [2,3]. Chinese manufacturers (Sinovel, Goldwind and Dongfang Electric) entered the elite list of top 10 global wind turbine manufacturers [4].

China has an estimated potential of 2680 GW onshore and 180 GW offshore in North and South-Eastern coastal areas. The National Energy Administration of China announced a target of 100 GW of wind installed capacity by 2015, 200 GW by 2020, 400 GW by 2030 and 1000 GW by 2050 [5]. Although these targets are enormous in terms of installed capacity and require almost 12 trillion RMB of investments, they are expected to address the rather moderate percentage of 17% of the electricity demand in China by 2050.

The development of wind energy in China has started through technology transfer based on joint venture activities due to the enormous initial capital investment and complexity of wind power technology [6]. Today the investment interest from all around the world remains high.

Although wind power capacity has increased rapidly China should improve the exploitation of wind power, by upgrading transmission infrastructure and reducing wind energy curtailment. In recent years, only a part of wind installed capacity is integrated into the grid [7,8]. Inadequacy of the power transmission grid, the absence of economic incentives for the development of transmission lines and the delays on the approval and development of the transmission lines lead to a significant mismatch between wind installed capacity and wind generation [9].

More and above, according to the State Electricity Regulatory Commission's (SERC) report, in the first 6 months of 2010, wind curtailment reached as high as 2776 GWh, accounting for about 10% of China's total wind power generation [10]. Wind energy curtailment may be higher in regions and subregions with high accumulation of wind farms. Today more than 80% of the wind installed capacity is located in the northern part of China. In 2011, wind energy curtailment was 17.6% in Northeast China, 13.7% in North China and 19.9% in Northwest China [8].

Uncertainties are encountered in most innovative entrepreneurial attempts, inducing a higher or lower risk to the investment under consideration. In the field of renewable energy applications, technological improvements and the introduction of different support schemes have alleviated to a great extent relevant risks, leading to the rapid deployment of renewable electricity, especially of wind farms, worldwide. However, investment risks are still present in all renewable energy projects and led to the development of various risk management instruments such as contracts, insurance, risk transfer, etc. as an essential part of a sound market [11]. Besides investment risks, uncertainty is a critical factor preventing reliable policy assessments for the relative attractiveness of technologies and/or the suitability of different regions for the deployment of these technologies.

In the particular case of wind energy, profitability depends on various uncertain parameters, such as wind velocity [12], financial aspects and operational factors [13], farm capacity and cost breakdown [14]. It is clear that for a specific project, in a given site in a particular time period, the information acquired by the interested investor might practically remove these uncertainties. Thus, uncertainty problems are raised mostly in the pre-decision stage for investors exploring new markets and for policy makers trying to adapt support schemes and other interventions to regional particularities. In these cases, the profitability of wind farms is a random outcome resulting as the joint effect of the variability of each single uncertain factor. Therefore traditional methods of uncertainty treatment, such as scenario approaches and sensitivity analysis, are not effective to handle this type of multiple eventualities. Besides, they are not able to identify a measure characterizing the associated profitability risk. Monte Carlo simulation is among the most frequently used methods for the treatment of such type of uncertainty [15]. It relies on random sampling of values for all the uncertain parameters, in order to obtain confidence estimates about the output variable. In practice, a wide variety of simpler or more complex simulation models have been developed in order to estimate risks related with unknown parameters [16]. Characteristic applications of the method for evaluating the profitability of energy projects include energy planning [17], retrofit investments in buildings [17], RES projects in relation to support mechanisms [18] and wind farms [19].

The scope of this paper is to analyze the profitability of wind farm investments in China by taking into consideration the most important of the above uncertain parameters, along with information about the wind potential in the country obtained by the Mesoscale Weather Prediction Model. For this purpose, the

profitability of wind farms in China's major geographical divisions is analyzed using a Monte Carlo simulation. Since each division is assigned with a different benchmark feed-in tariff and different infrastructures, the analysis is also intended to evaluate the existing feed in tariffs scheme and also to analyze the effect of grid accessibility issues and wind curtailment on the profitability of wind investments. The obtained results illustrate in quantitative terms the expected profitability in each region and can provide valuable information to potential investors while guiding the Chinese government for identifying policies and interventions, aiming at the large scale wind energy exploitation.

2. Uncertainty analysis in wind farm profitability assessment

The uncertain parameters affecting the financial profitability of wind farms can be classified in two major categories:

- *Internal or site-dependent parameters* principally include technological and site-specific factors, characterizing each particular project, such as the wind potential, investment cost, grid issues like accessibility to the grid and wind energy curtailment. Moreover feed-in tariffs, although influenced by the economic environment, are also dependent on the site, following the division of the country in zones of different benchmark feed-in tariffs.
- *External or economy-related parameters* include the factors depending on the economic environment in China, such as the type of support scheme, the time value of money, the terms of the loan and the taxes.

Economic parameters are generally affected by the macroeconomic environment in the country or in a wider economic zone and are independent of the internal parameters. Far from this, most of the internal parameters are correlated with each other, as the site is the most important factor affecting investment cost and wind farm efficiency. Also grid accessibility and wind energy curtailment, both strongly affecting the viability of the project, are related with the site selection.

It is clear that the uncertainty of most of these parameters can be removed to a great extent by each single investor acquiring project-specific information and conducting analytical measurements and feasibility studies in the preselected site(s). However, for big investment groups considering initially only rough figures of the Chinese territory in order to take decisions whether and where to invest as well as for policy makers seeking to set incentives or priorities for infrastructure works in different regions, it is preferable to look at fuzzy intervals of these parameters instead of crisp values.

For such a policy context, the profitability of a wind farm can be approximated only by considering the simultaneous variation of all these – initially uncertain – parameters. Monte Carlo simulation is an effective approach to perform a what-if analysis with many hundreds of iterations, each representing a randomly selected set of the examined uncertain parameters, in order to produce the probability distribution of the profitability index.

The modeling procedure through Monte Carlo simulation includes the following steps:

1. specify the uncertain input parameters,
2. select a distribution to describe the possible value range for each uncertain input parameter,
3. generate the output variable from randomly selecting input values on the basis of the selected distribution for a large number of iterations,

Depending on the type of uncertainty, randomness is approximated through appropriate distributions which may result directly from statistical or experimental data or from subjective judgments. Among the most commonly used distributions is the uniform distribution, defining only the minimum and maximum value of the possible range of values of the uncertain parameter. If there is knowledge about a most likely value or midpoint, in addition to a range, a triangular distribution may be assigned or the standard distribution assuming a symmetrical deviation from a given mean value. Other characteristic distributions are the normal, gamma, beta, Weibul, as well as logarithmic distributions for higher degrees of uncertainty [19].

3. Specification and interrelation of site-dependent parameters

The location of the wind farm is a crucial factor for the investment decision. A number of parameters determining technical efficiency and the feasibility of the wind farm depend on site-specific characteristics and are strongly interrelated to each other. For the systematic investigation of all these parameters we proceed to the definition of typical projects by taking into account administrative divisions and empirical data.

3.1. Benchmark feed-in tariffs

The point of departure for the present analysis is the announcement[2] issued by the central government, specifying the benchmark on-grid feed-in-tariffs (FITs) for wind power plants in the four regions – categories shown in Fig. 1.

In this connection, the analysis follows the four regions – categories which have been specified, as follows:

- *"Category I,"* with benchmark FIT 0.51 CNY for sites located in Inner Mongolia autonomous region except: Chifeng, Tongliao, Xing'anmeng, Hulunbeier; Xinjiang Uygur autonomous region: Urumqi, Yili, Karamay,and Shihezi.
- *"Category II,"* with benchmark FIT 0.54 CNY for sites located in Hebei province: Zhangjiakou, Chengde; Inner Mongolia autonomous region: Chifeng, Tongliao, Xing'anmeng, Hulunbeier; Gansu province: Zhangye, Jiayuguan,and Jiu.
- *"Category III,"* with benchmark FIT 0.58 CNY for sites located in Jilin province: Baicheng, Songyuan; Heilongjiang province: Jixi, Shuangyashan, Qitaihe, Suihua, Yichun, Daxinganling region, Gansu province except Zhangye, Jiayuguan, Jiuquan, Xinjiang autonomous region except Urumqi, Yili, Changji, Karamay, Shihezi,and Ningxia Hui autonomous region.
- *"Category IV,"* with benchmark FIT 0.61 CNY for sites located in all the other parts of China not mentioned above.

3.2. Wind potential

Information about the wind potential in the above four regions has been provided by the application of a Numerical Weather Prediction (NWP) model. In this connection, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) developed at the US Naval Research Laboratory is used [21]. COAMPS is a three-dimensional non-hydrostatic model that has been used for operational forecasting since 1996 for a wide range of research purposes for both idealized as well as real data simulations. Appropriate

[2] Available on ⟨http://en.in-en.com/article/News/Renewable/html/200907251-3592.html⟩.

adjustment of the numerical parameters, systematic application on a yearly basis and thorough analysis and processing of wind characteristics provide simultaneous wind speed time series at the mesoscale over the whole territory of interest. High resolution of 3 km covers promising windy areas for potential wind farm developments, while lower resolutions of 9 and 27 km were used for the remaining area. This information is used for the development of the Eolian map of China represented by the wind capacity factor at 30 m above ground level, shown in Fig. 2.

Based on this approach 500 sites of wind energy development were randomly selected from all four categories of regions, following the location of the existing wind farms, as shown in Fig. 3, and the capacity factor (CF) was estimated for each site. From this analysis it has been shown that in all four regions there are sites with good wind potential. It seems that categories I and II are more windy areas in comparison with categories III and IV.

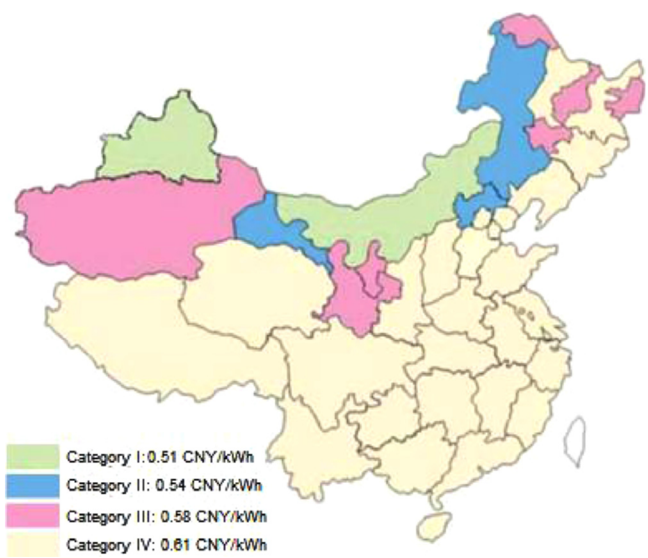

Fig. 1. Benchmark feed-in tariffs for onshore wind power [20].

This means that wider areas in categories I and II are considered as suitable areas for wind development. Far from that in category IV, which is the largest area and enjoys the highest feed in tariffs, there are large areas mainly located in the mainland with low wind resources, but also some very windy areas along the densely populated East coast and the mountainous South West areas. Although the latter is not favorable for wind energy development due to high altitude and consequently low air density, complex topography and accessibility issues, the former is one of the most promising wider areas in China: high wind potential, grid accessibility and geographical match with highly developed urban areas characterized by high energy consumption are some of the advantages of the East Coast. On the other hand, due to conflicts with other land uses and high population density, smaller wind farms are being developed, in comparison with the other site-categories. Indeed especially in categories I and II, which are rather rural isolated areas, land availability could permit the development of huge wind farms, with lower cost due to economies of scale.

3.3. Investment cost

Investment cost of wind energy may vary considerably from country to country and from site to site. Many reports [23–27] address the key parameters of wind energy cost and discuss the wind energy economics. Most of these reports use the levelized cost of energy index, to make comparisons between low, medium and high wind potential sites, or comparisons with conventional energy sources [25,26]. Levelized cost of energy is affected by the capital cost, operation and maintenance cost, time value of money and energy yield (capacity factor) [25]. A comparative analysis is sometimes performed in low wind areas, medium wind areas and coastal areas [25] or on onshore and offshore wind energy [27]. It is shown that the capital cost or investment cost varies, not only with the size of the project due to economies of scale but also with the exact location of the site which affects construction expenses and infrastructures upgrading. In this sense, there is an interrelation between investment cost and available wind resources.

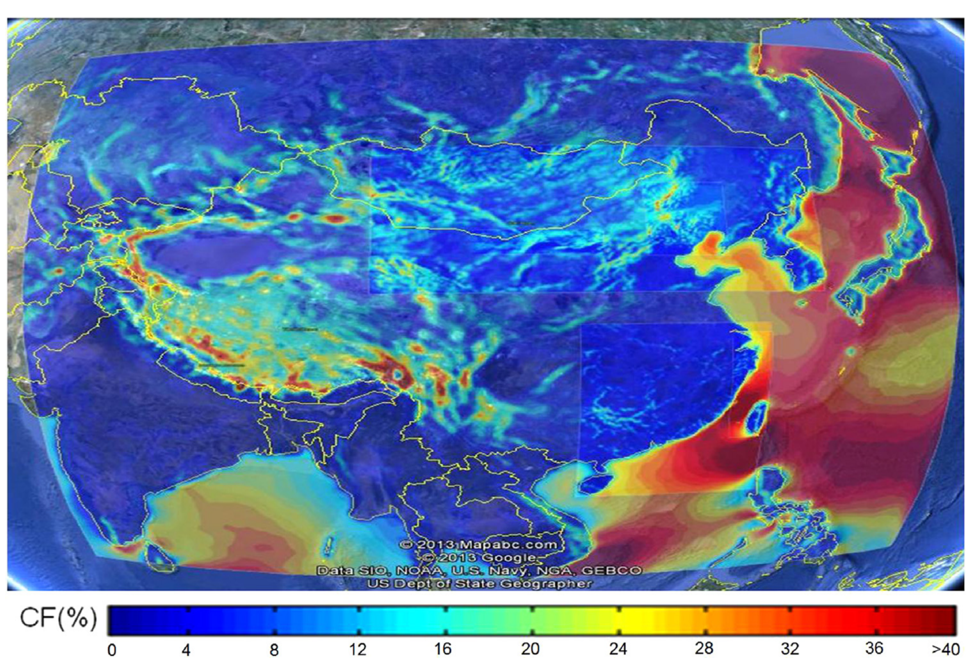

Fig. 2. Capacity factor at 30 m above ground level in China, based on wind data reproduced by mesoscale weather prediction application and on representative wind turbines' power curves [22].

Fig. 3. Wind farms sites in China. Available on: ⟨http://www.thewindpower.net/country_maps_en_9_china.php⟩.

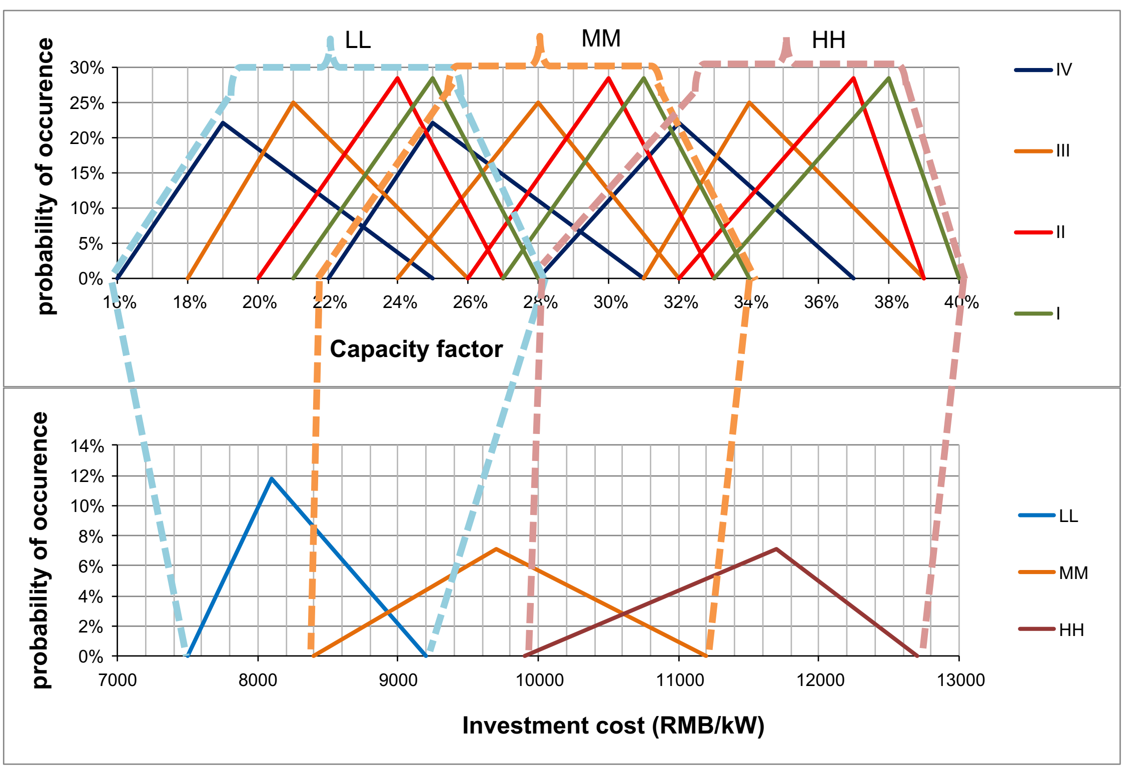

Fig. 4. Modeling of the capacity factor and investment cost in regions I–IV, and typical wind projects LL, MM and HH.

Both the cost of the wind turbine and the cost of upgrading the relative infrastructures are related with the site and the wind potential. Today, all the wind turbines manufacturers offer specific wind turbine classes, categorized in reference with the wind potential characteristics (average wind speed and turbulence level). Always lower wind speed sites are characterized by lower turbulence and lead to low class and cheaper wind turbines. More and above, higher investment cost is expected in cases where the parallel upgrading of relative infrastructures is required [28]. Especially, in some developing countries or new wind energy markets [29] spatial planning issues are not yet clarified and may cause delays in the licensing and construction of infrastructures, which in turn result in further unexpected costs. More and above, wind energy is often developed in remote areas, which means weak grid or saturated grid in windy areas with significant wind penetration. Then, additional costs for reinforcement of the regional transmission grid may be required.

Thus, in macroscale analysis, investment cost is very often introduced by a range of values, reflecting both the characteristics of the site and the cost of technology. In general, investment cost can be decomposed into different parts. In typical cases, without large scale works for infrastructures (grid and roads), the cost of wind turbines is 75% of the total investment cost, while 9% is attributed to grid connection, 6.5% to foundation, 3.9% to cost of land, 1% to roads construction and others [25].

Today, in the top wind markets in the world, most of the good onshore sites have already been developed, and the trend is to develop wind farms in low or moderate wind potential sites close to existing infrastructures and trying to optimize the design and the performance of the projects. These projects may be profitable under the condition of low infrastructures costs, and low cost of money (low interest rates) as well. At the other side today European wind energy developers turn their glance on offshore projects expecting higher capacity factor [30], even with higher investment cost [31].

Far from this, the investment cost is also related to the size of wind farm. In large wind farms, economies of scale may lead to reduced cost. In China most of category I and the west part of category III regions are considered as isolated windy areas with low population density, ideal for the development of large wind farms, but far from demand centers. In some of these cases, significant and expensive improvements of infrastructures may be required and lead to higher cost. The massive wind energy development in these areas may reduce these additional costs per kW installed. Category II (especially the eastern part of this region) seems to be an ideal place for wind development thanks to abundant wind potential, and to the moderate distance to the east urban and industrial centers. Finally, category IV and the rest of category III are closer to demand centers, with high population density. In the latter cases, lower additional cost for infrastructures may be required but the value of land is higher.

3.4. Grid accessibility and wind energy curtailment

China's wind power resources are mainly located in North, North-West and North East regions, but the main power demand centers are located along the eastern coastal region. This geographic mismatch of wind energy resources and power consumption instigates grid connectivity and wind curtailment problems [32], which are two of the most important parameters affecting the economic feasibility of wind farm investments in China. There are wind farms which have been installed and are not set into operation waiting for the extension or upgrading of the grid. By the end of 2011 total installed capacity of wind power in China reached 62.36 GW and only 47.84 GW was connected to the grid, or 76.7%, which was quite higher compared to the 69.9% recorded in 2010 [33].

Additionally, investors face wind energy curtailment also in areas with hyper-accumulation of wind farms. In some cases, it may reach up to 30% and wind farm operators are suffering significant losses of revenues. Regionally, curtailment is more intense in northern, northwestern and northeastern China. A statistical analysis showed that curtailment was more outspread in eastern Inner Mongolia (included in category II) and Jilin (category III), which had a curtailment rate of over 20%. The level of curtailment was also high in western Inner Mongolia (category I), Gansu and Heilongjiang (category II, III), each with a curtailment rate of more than 10% [32,33].

The effect that these two parameters, related with insufficient infrastructures, may have on wind farms profitability in China is examined in the subsequent financial analysis.

4. Modeling uncertainties in wind farm profitability analysis

4.1. Site-dependent parameters

The preceding discussion has shown that the cost of wind farms and the capacity factor are closely related to each other. Therefore, in order to better approximate their interrelation, three typical wind farm projects are examined in each region. The analysis of typical projects may provide valuable support to the design of the legislative framework, of feed-in-tariffs and relative regulations, in the framework of a national energy policy. In this connection, the following typical wind farm projects are defined:

- low wind potential – low investment cost (LL),
- moderate wind potential – moderate investment cost (MM),
- high wind potential – high investment cost (HH).

It is clear that in the whole Chinese territory, there exist sites with low wind potential and high investment cost. However, for these sites there is apparently no interest for wind energy investments. On the other hand, there may be sites with high wind potential and rather low cost. These cases are obviously the ideal, but they are considered as the exception that proves the rule, and probably, they have already been exploited. The design of the incentives, which is given for the wind energy development, is not based on such specific ideal or unfavorable conditions.

Triangular distributions are selected to represent the variation of the capacity factor and investment cost in each region and each type of project, as graphically depicted in Fig. 4. It can be seen that each triangular distribution is delimited by three values: a minimum at the left side (L), a maximum at the right (R) and a most probable or mid value (M) for each case. Moreover, it is worth noticing that there are significant overlaps between the value ranges of the defined typical projects in different site categories.

The values delimiting the triangular distribution for the capacity factor are presented in Table 1 and have been drawn from the analysis of data recorded for the 500 randomly selected sites of the

Table 1
Triangular distribution for the wind capacity factor (%).

Limit values	I			II			III			IV		
	LL (%)	MM (%)	HH (%)	LL (%)	MM (%)	HH (%)	LL (%)	MM (%)	HH (%)	LL (%)	MM (%)	HH (%)
L	20	26	32	19	25	31	18	23	30	17	22	29
M	26	32	39	24	30	37	22	29	34	20	27	33
R	28	34	40	27	33	39	26	31	38	25	30	37

Table 2
Triangular distribution for investment cost (RMB/kW).

Limit values	LL	MM	HH
L	7500	8400	9900
M	8100	9700	11,700
R	9200	11,200	12,700

Table 3
Triangular distribution for wind energy absorption rate (%).

Limit values (%)	I	II	III	IV
L	70	70	70	70
M	70	80	80	90
R	100	100	100	100

Eolian map. Similarly, the values delimiting the triangular distribution for the investment cost of wind farms, presented in Table 2 are also based on empirical data derived from already installed and ongoing projects in China. It should be noted that these values are lower compared to those recorded in North Europe, which typically vary between 1100 and 1400€/kW [25].

Feed-in-tariffs are defined by using a dynamic triangular distribution trying to approximate the investors' behavior. It is acknowledged that investors tend to depress their bid to the benchmark limit, in order to increase their chances of being selected. However, when the wind potential is not so promising and/or expensive infrastructures are needed, they are obliged to set a higher bid in order to ensure the viability of their project. Thus, in all regions, a uniform distribution is selected, which is delimited by a lower value set equal to the corresponding benchmark FIT, and a higher value set at a level which is by 20% higher. The mid-value lies within this range and is calculated in each iteration, in accordance with the randomly selected capacity factor, i.e. the higher the capacity factor, the closer to the benchmark tariff the mid-value.

Finally, the uncertainty associated with wind energy curtailment and grid accessibility has been modeled by using triangular distributions. The same limits were used in all four regions, but the mid-value is differentiated among the four regions, based on the statistical data provided by various reports [7,8,10,32,33]. The assumed distributions are presented in Tables 3 and 4 and show that projects in category I face a higher risk of curtailment and bigger delays for accessing the grid, whereas the lowest risks are foreseen for projects in category IV.

It should be noted that other project-related parameters affecting the profitability of the typical projects are considered to be exempt from any uncertainty. Namely, the lifetime of wind farms is assumed to be 20 years and the operational cost is considered to be equal to 1.5% of the investment cost.

4.2. Macroeconomic parameters

Most of the economic parameters involved in the financial model are assumed to be known with certainty and are the same for all wind farm types, as shown in Table 5.

The only exception is the interest rate of the loan provided to the investor which is assumed to vary between 3% and 5%, following a symmetric triangular distribution (mid-value 4%). This variation is representative of the unstable economic environment which is faced by policy makers and investors who are called to trace policies and make their medium term plans.

Table 4
Triangular distribution for grid accessibility (years after the installation for the connection to the grid).

Limit values	I	II	III	IV
L	0	0	0	0
M	2	2	1.5	1
R	3	3	3	3

Table 5
Values (%) of economic parameters.

Parameter	All types of projects
Tax	15
Depreciation rate	5
Own capitals/loan	30/70

5. Results and discussion

The study aims at assessing the profitability of the typical projects (LL, MM and HH) in each region (I–IV) under the conditions of risk defined in the previous section. The analysis is performed in three

Table 6
Average IRR (%) and IRR range (%) with confidence interval 90% (ignoring grid-related risks).

Average IRR (IRR range with confidence interval 90%)	LL	MM	HH
Category I	**14.9** (11.3–18.1)	**16.6** (12.4–20.3)	**17.4** (13.7–20.8)
Category II	**15.4** (11.6–18.6)	**17.5** (13.4–21.3)	**18.5** (14.7–22.1)
Category III	**15.0** (10.9–19.1)	**18.1** (13.2–22.2)	**19.8** (15.5–23.9)
Category IV	**14.4** (9.4–18.7)	**17.2** (12.2–22.1)	**19.1** (14.9–23)

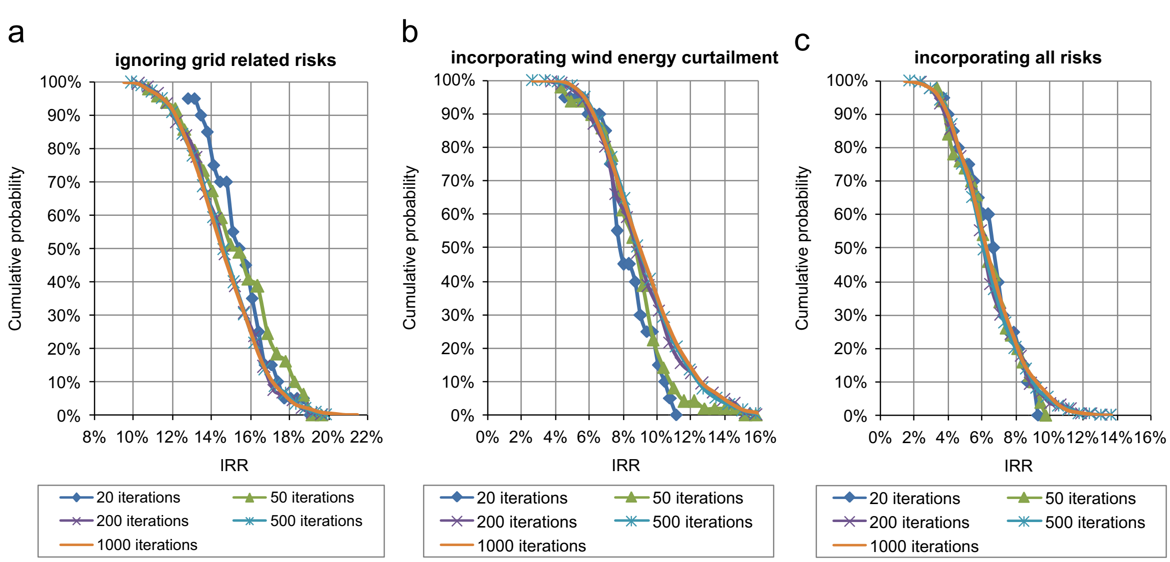

Fig. 5. The effect of the number of iterations on the results (project type LL, region I): (a) ignoring grid-related uncertainties (four uncertain parameters), (b) incorporating risk for wind energy curtailment (five uncertain parameters), and (c) incorporating all risks (six uncertain parameters).

consecutive stages in order to disclose the impact of the examined uncertain variables on wind farm profitability:

1. by ignoring all grid-related risks,
2. by adding the risk of wind energy curtailment during operation of the wind farm,
3. by adding the risk of excess delays in the connection to the grid and the start of the wind farms commercial operation.

The aim was not only to assess the attractiveness of each region under the specified benchmark FITs, but also to indicate the necessity to speed up upgrading of grid infrastructures in each region.

5.1. Calibration of the Monte Carlo simulation

Before proceeding to the analysis the developed tool is calibrated with respect to the number of iterations required to provide a reliable representation of probability distributions of the profitability index, under the specific conditions of risk.

Specifically, five tests have been performed, with "20," "50," "200," "500" and "1000" iterations in each analytical step.

Since the types of distributions and the width of value ranges of the uncertain parameters are the same in the three different types of projects (LL, MM and HH) as well as in the four different regions (I–IV) the calibration procedure is implemented in only one typical project, namely for project LL and region I.

In the first step, the examined uncertain parameters are the following:

- wind capacity factor,
- investment cost,
- interest rate,
- feed-in-tariff.

In the second step the number of the examined parameters is increased to 5, as soon as the absorption rate is introduced. Finally, in the third step, the number of the uncertain parameters is increased to 6 with the introduction of the factor concerning grid accessibility. As shown in Fig. 5, in all three cases, of 200 iterations seems to be enough for accurately representing the probability distribution of the calculated profitability index (IRR). Moreover, the two curves of "500" and "1000" iterations are almost identical.

However, in the analysis that follows "1000" iterations are used as the additional computational cost is negligible.

5.2. Evaluation of wind farm investments in China, ignoring grid-related risk

First, the analysis has assumed that there is no risk of delays for the connection of the farm to the grid and of reduced absorption of the produced electricity. The results obtained from the Monte Carlo simulation are summarized in Table 6, indicating the average of the expected Internal Rate of Return IRR and the range of the expected Internal Rate of Return (IRR) for each typical case and for a confidence level of 90%.

It can be seen that the development of wind energy is a very profitable business opportunity for the whole Chinese territory as the calculated IRR in all regions lies, with almost 100% certainty, above 10%. As expected, the most attractive investment is the "HH" wind project, with IRR reaching 21–24% for the examined level of confidence. However the "MM" and "LL" projects are also attractive investments ensuring a very satisfactory performance,

Table 7
Average IRR (%) and range (%) with confidence interval 90% (incorporating risk for wind energy curtailment).

Average IRR (IRR range with confidence interval 90%)	LL	MM	HH
Category I	**9.4** (5.5–13.4)	**10.7** (6.2–15.3)	**11.4** (7.2–15.8)
Category II	**10.8** (6.7–14.7)	**12.3** (7.9–16.5)	**13.1** (8.8–17.1)
Category III	**10.5** (6.2–14.7)	**12.7** (8–17.4)	**14.2** (9.7–18.9)
Category IV	**10.7** (5.7–15.5)	**13.2** (7.9–18.2)	**14.7** (9.5–19.5)

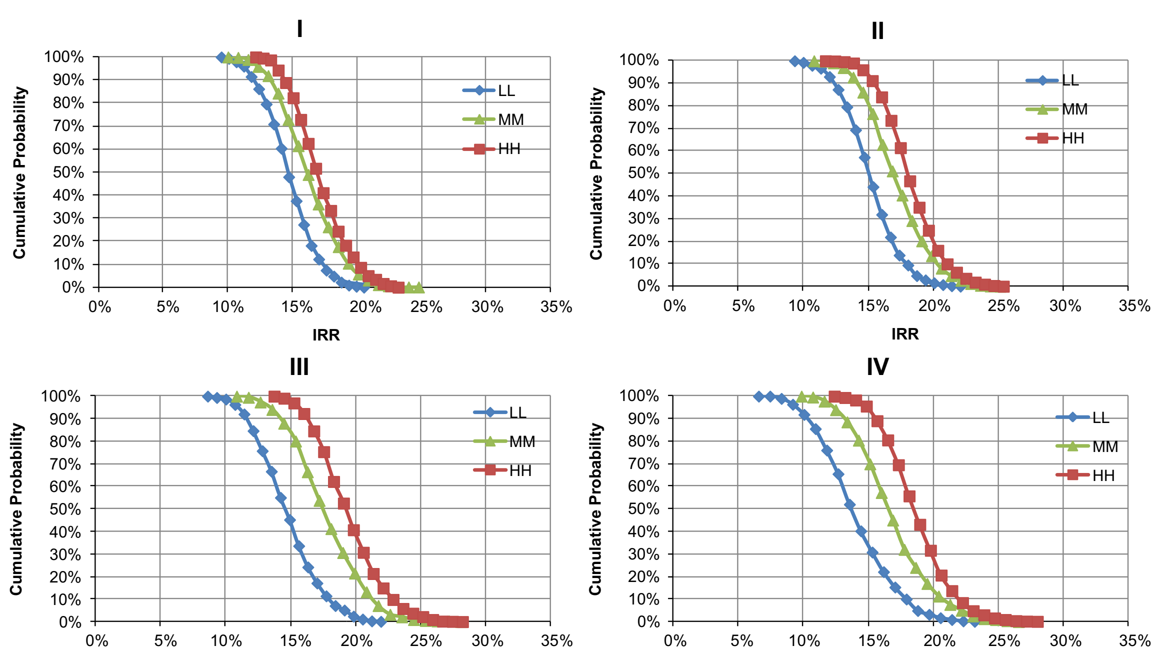

Fig. 6. Cumulative probabilities of IRR of wind projects in China for regions I–IV, and typical wind projects LL, MM and HH (ignoring grid-related risks).

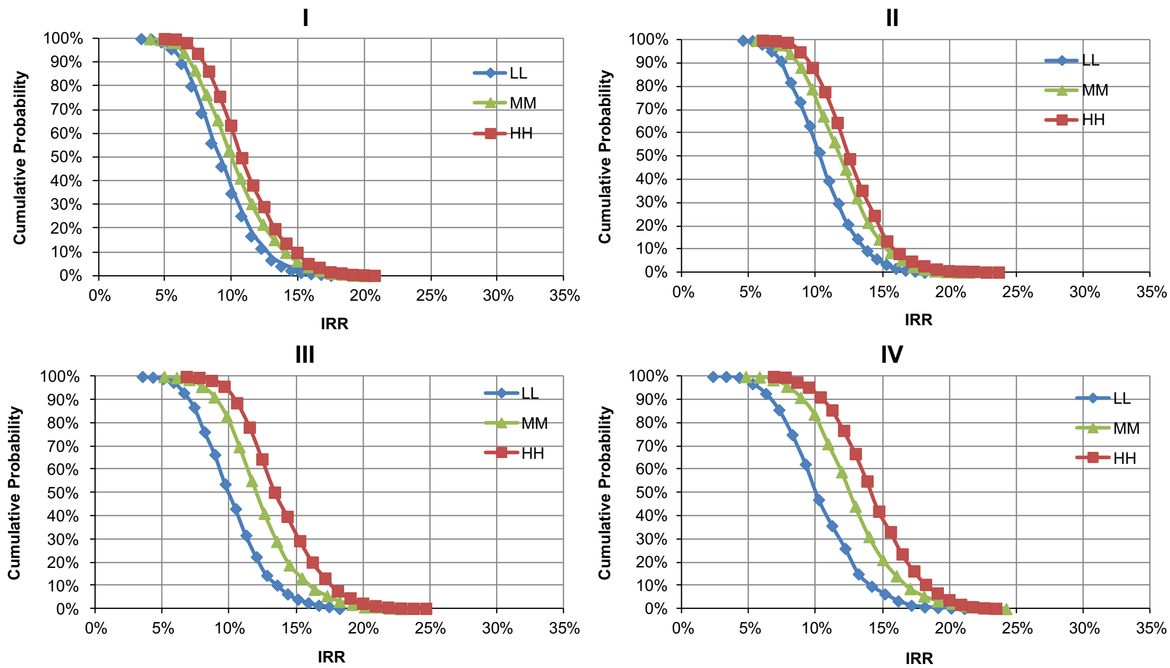

Fig. 7. Cumulative probabilities of IRR of wind projects in China for regions I–IV, and typical wind projects LL, MM and HH (incorporating risk for wind energy curtailment).

Table 8
Range of IRR (%) with confidence interval 90% (incorporating all risks).

Average IRR (IRR range with confidence interval 90%)	LL	MM	HH
Category I	**6.9** (3.6–10.4)	**7.6** (4–11.4)	**8.2** (4.7–12.1)
Category II	**7.7** (4.4–10.9)	**8.6** (5.1–12.4)	**9.3** (5.8–12.7)
Category III	**7.4** (4–10.7)	**9** (5.3–12.6)	**9.9** (6.2–13.6)
Category IV	**7.8** (3.7–11.4)	**9.4** (5.2–13.3)	**10.4** (6.4–14.5)

without excess profits and without practical risk for the IRR to fall below 10%. In addition the above outcome shows that the benchmark FITs fixed by the Chinese government are in principle effective, giving incentives to develop wind energy in all regions.

Fig. 6 provides an overview of the obtained results by presenting, for each region, the cumulative distribution functions of the IRR of the examined typical projects. It can be seen that by moving from region I to region IV the range of IRR values widens, as does the difference between the typical projects concerning the probability to achieve a certain IRR. This is attributed to the wider interval of FITs defined for this region, based on a higher benchmark value basis (0.61 CNY).

5.3. *Introducing the risk of wind energy curtailment*

In the second step, the risk of wind energy curtailment in China is analyzed. Based on the examined confidence interval of 90%, the results presented in Table 7 show that the lower end of IRR is reduced by an average of 5.3%, while the maximum IRR is reduced by an average of 4.3%. This means that the risk of facing an absorption rate in the range of 70–100% of total production may significantly reduce the attractiveness of the investments in all examined case studies. However, projects of type HH remain quite attractive investments, especially in regions III and IV, where the lower IRR value is very close to 10%. On the contrary projects of type LL are, in all regions, the most vulnerable to energy curtailment.

Moreover, the differentiation between the four regions becomes more pronounced, since as indicated by the values of Table 4, the risk of reduced absorption rates is higher in regions I and II.

The obtained results, as graphically depicted in Fig. 7, confirm the above remarks and show the same trend for a wider IRR value range in regions III and IV.

5.4. *Introducing the risk of delays to access the grid*

Finally the combined effect of all uncertain factors, including wind energy curtailment and delays in the implementation of grid connections, on the profitability of the investments is examined. Obviously, as can be seen in Table 8, the expected IRR is further reduced. In this case, the average drop of IRR is 7.9% and 8.4% for the minimum and the maximum values of the first examined case, respectively.

It is found that all types of projects in all four regions present a rather marginal profitability, together with a high risk for extremely low rates of return. Moreover, Fig. 8 shows that the range of IRR values is in all cases small, denoting a high degree of certainty about an unfavorable outcome.

5.5. *Discussion*

All the obtained results are summarized in Fig. 9, depicting the sharp drop of the profitability index by incorporating grid related

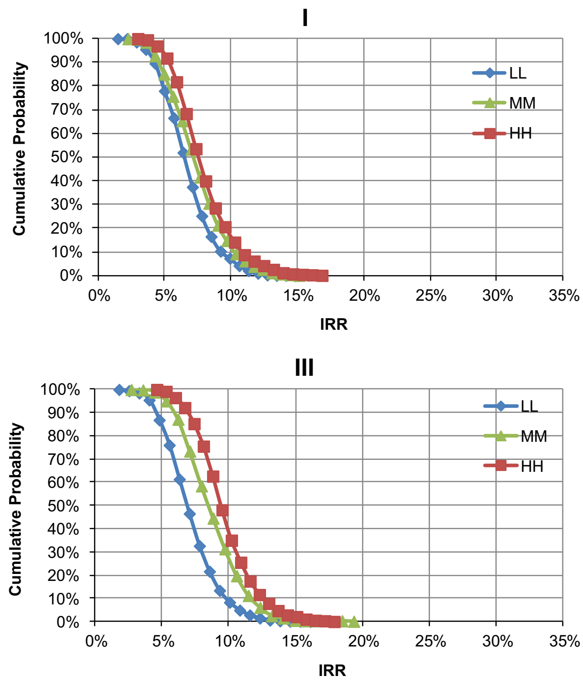

Fig. 8. Cumulative probabilities of IRR of wind projects in China for regions I–IV, and typical wind projects LL, MM and HH (incorporating all risks).

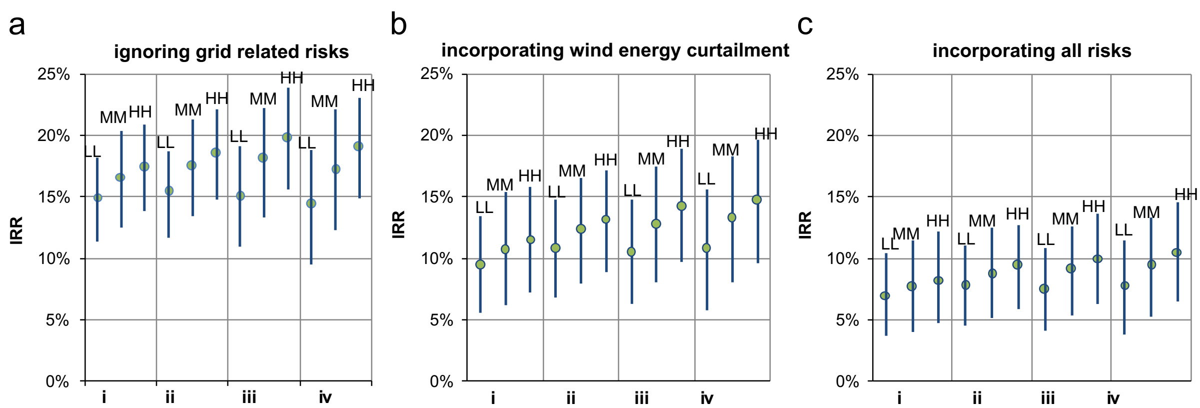

Fig. 9. Average IRR and range with confidence interval 90% (a) ignoring grid uncertainties, (b) incorporating risk for wind energy curtailment, and (c) incorporating all risks.

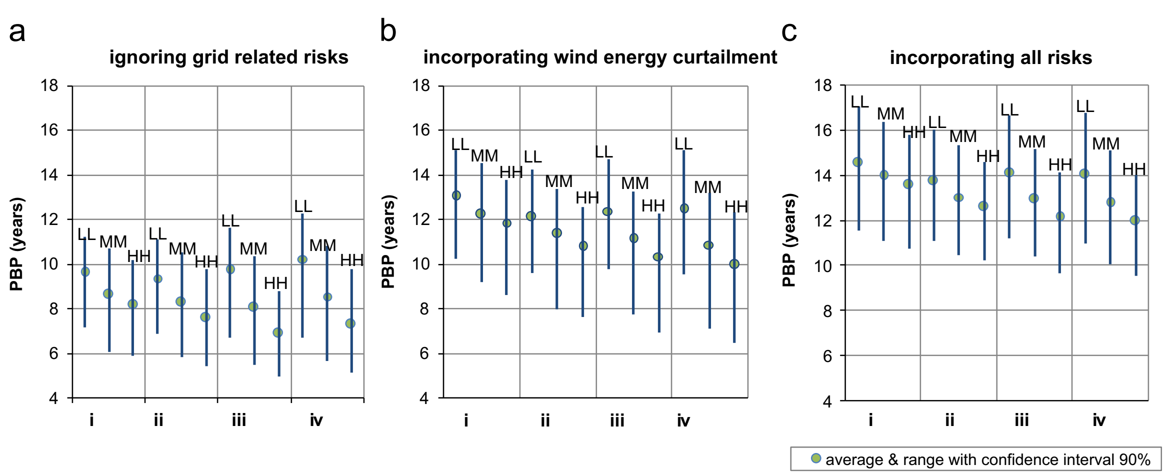

Fig. 10. Average PBP and range with confidence interval 90%: (a) ignoring grid uncertainties, (b) incorporating risk for wind energy curtailment, and (c) incorporating all risks.

risks. It is also shown that, besides the assumption that sites with a higher wind potential are usually associated with a higher investment cost, the energy yield directly associated with the capacity factor remains a critical parameter for wind farm profitability. In all regions, the profitability is increased for higher capacity factor. In the examined typical cases, the difference in the IRR

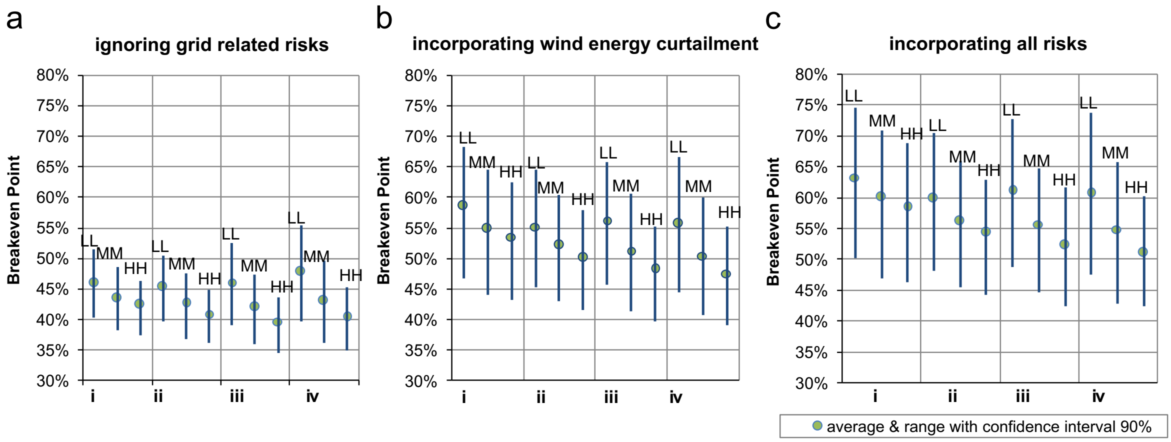

Fig. 11. Average Breakeven point and range with confidence interval 90%: (a) ignoring grid uncertainties, (b) incorporating risk for wind energy curtailment, and (c) incorporating all risks.

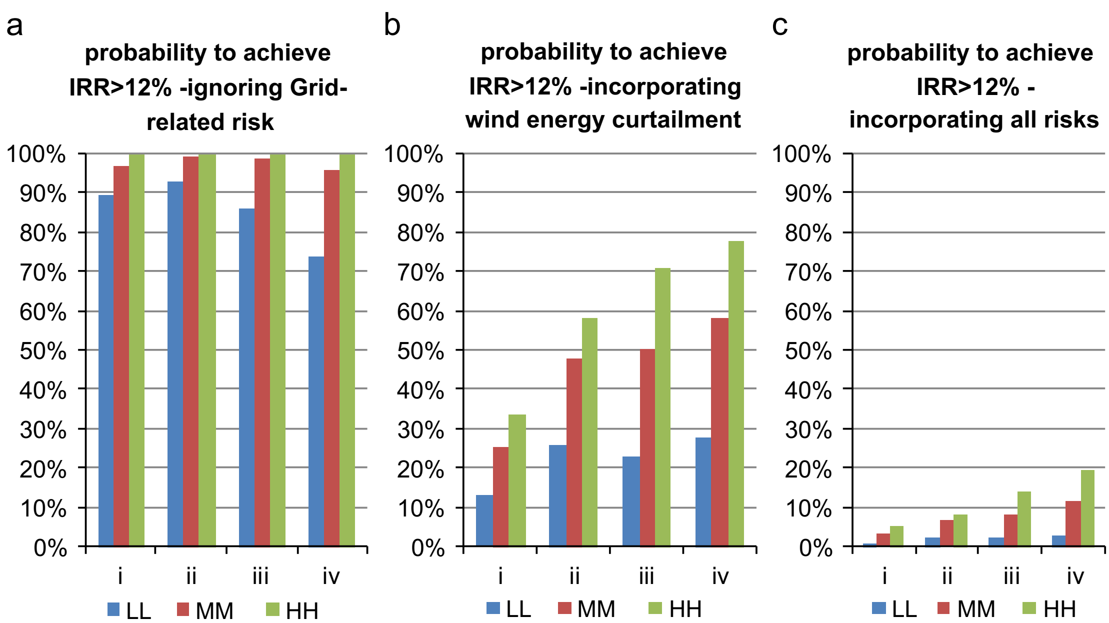

Fig. 12. Probability to achieve IRR > 12%, for wind projects in China in regions I–IV, and typical wind projects LL, MM and HH: (a) ignoring grid-related risk, (b) incorporating wind energy curtailment and (c) incorporating all risks.

between HH and LL projects varies between 2% and 5%. The importance of the capacity factor is decreased when grid-related risks are incorporated. In this case (Fig. 9c) lower differences are expected among the three types of projects (HH, MM, LL). Finally it is clearly discernible that all regions present similar profitability rates, proving the fairness of the established FIT system.

It should be noted that the range of probable IRR values for 90% confidence level is quite large (7–10% from upper to lower limit), reflecting the respective variation of the uncertain input variables. Since the assumed limit values rely on real observations, there is no sense in carrying out a sensitivity analysis. Instead it is necessary in a next step of this research to focus on smaller geographical areas where the level of uncertainty is lower, in order to give more helpful insights to interested investors.

Alternative profitability indices, namely the simple Payback period (PBP) of each typical project and the Breakeven point (BEP), defined in terms of the percentage electricity production compared to the maximum production corresponding to the capacity factor considered in each case have also been calculated and are presented in Figs. 10 and 11 respectively. When grid related risks are ignored, in all the examined cases, the average simple PBP varies between 6.9 and 10.2 years (Fig. 10a), and the BEP between 40 and 48% (Fig. 11a). When all risks are incorporated, the average values are increased to 12–14.6 years for the simple PBP (Fig. 10c) and to 51–63% for the BEP (Fig. 11c). As expected, the same conclusions can be drawn regarding the profitability of the different typical projects in different regions.

Figs. 12–14 present in a more illustrative way the risk associated with the exploitation of wind energy in China. Three limit profitability values are used as a basis on which the projects and regions are compared: the probability for each type of project to present a value of IRR above 12%, a simple Payback period below 10 years and a Breakeven point above 50% are demonstrated to assess the attractiveness of wind energy investments in China. It can be seen that in an ideal situation, with a fully developed transmission grid, whole China would be an excellent host for

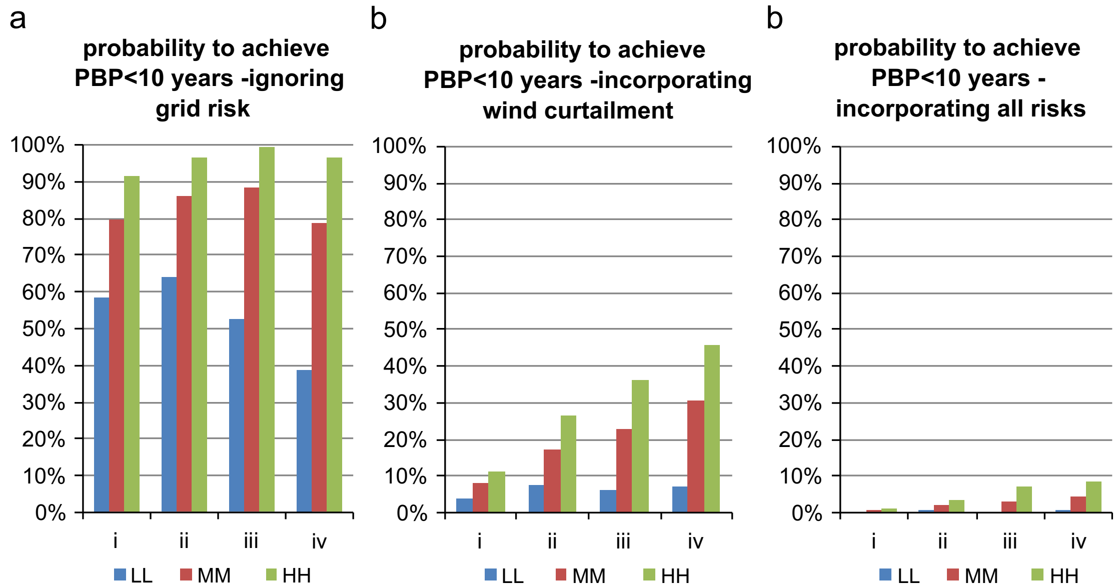

Fig. 13. Probability to achieve PBP < 10 years for wind projects in China in regions I–IV, and typical wind projects LL, MM and HH: (a) ignoring grid-related risk, (b) incorporating wind energy curtailment and (c) incorporating all risks.

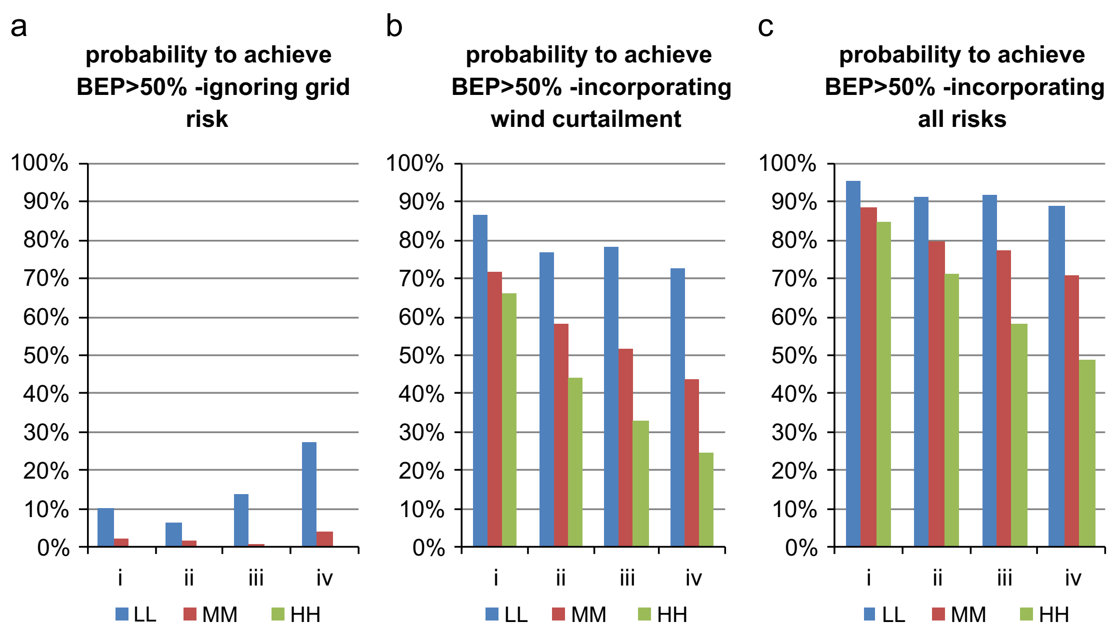

Fig. 14. Probability to reach Breakeven point > 50% for wind projects in China for regions I–IV, and typical wind projects LL, MM and HH: (a) ignoring grid-related risk, (b) incorporating wind energy curtailment and (c) incorporating all risks.

wind energy investments: The probabilities for projects in sites of medium and high wind potential to present a very satisfactory financial performance (IRR > 12% and simple PBP < 10 years) are in all regions above 80%, while in sites of low wind potential there are also good chances for a profitable investment. Accordingly, the probability for Breakeven point of the investment to lie at high production levels is minimal. However the real constraints of the actual grid lead to a sharp drop in the profitability of wind energy projects especially if, in addition to a delayed connection to the grid, there is a risk of reduced absorption during wind farm operation.

6. Conclusions

China has become a global leader in wind energy due to its remarkable wind potential, the development of a dynamic domestic manufacturing industry and the steadily increasing electricity demand imposing the need to shift towards renewable energy sources. The rapid deployment of wind farms proves the investors' big interest but at the same time calls for the urgent need to upgrade and extend network infrastructures.

The present paper has attempted to evaluate the attractiveness of wind energy investments in China by giving emphasis to the risks associated with wind farm installation and operation. The analysis relies on the administrative division of the country used to specify benchmark feed-in-tariffs. Besides the usual macroeconomic risks faced by investors, especially in times of economic turbulence, wind energy projects are associated with additional uncertainties related principally to site-specific factors. On top of this the high accumulation of wind farms in certain regions of China, together with inadequate transmission and distribution capacity, entails additional concern about the financial performance of these projects.

The obtained results confirm that China could be an ideal place for wind energy exploitation. In all administrative regions the financial performance of relevant investments is more than satisfactory, even if the wind potential is not very high. This proves that the proposed system of benchmark feed-in-tariffs is in the correct direction, as it encourages the dispersion of wind energy investments in the whole country. However, actual conditions of the network system are found to greatly reduce the attractiveness of wind energy investments. This is especially true for the northern regions of the country I and II, presenting high wind potential (hence, lower feed-in tariffs), lack of infrastructures (hence, delays of grid connections) and lower electricity demand (hence, higher curtailment rates). In these regions sites of a relatively low wind potential cannot be considered, under actual conditions, as a safe and appealing place for wind energy investments.

On the opposite side, region IV covers a very large part of the country and includes areas with totally different characteristics. This is the reason why the range of the calculated IRR values is the largest compared to all other regions. Especially the East Coast of China, which is mostly included in region IV, is characterized by abundant wind potential, good grid accessibility and high absorption rates, mainly due to the geographical match with the large load centers. Probably, it would be useful for the rational development of wind energy in China to distinguish the eastern coastline of Region IV and reconsider the given incentives.

It should be noted that the proposed approach aims to illustrate the effect of uncertain parameters on the profitability of wind energy projects, following the broad administrative division of China as regards the level of FIT. It is clear that by focusing on a smaller area, the profitability indices would vary in a smaller range of values and could provide a more robust support to investment decisions and policy making.

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